

Mars Polar Energy Balance Science for the Next Decade

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Abstract:

In 1966, Leighton and Murray used polar energy balance calculations to predict that the Mars seasonal polar caps were composed of CO₂ ice, and not H₂O ice as had been the common belief for hundreds of years. Over four decades later, the pursuit of detailed scientific understanding of the polar energy balance continues to be integral to elucidating the mysteries of Mars and its polar regions. At present, continued research in this area is significantly impeded by the scarcity or lack of data at appropriate spatial and temporal resolutions, fundamental gaps in the understanding of the properties and behavior of realistic CO₂ ice (i.e., that which is contaminated by water ice and/or dust) under Mars conditions, and a lack of research funding options that are willing to support inter-disciplinary Mars studies that involve equal measures of numerical modeling, data analysis, and/or laboratory work. Choosing not to remove or minimize these impediments during the next decade would be significantly detrimental to continued progress toward understanding the climate and its geologic implications throughout current, prior, and future epochs of Mars history. To address these deficiencies a three-fold approach is recommended for the coming decade: (1) increase the emphasis within NASA's R&A programs to specifically support CO₂ ice laboratory experimentation and inter-disciplinary investigations involving multiple techniques (any well-justified combination of modeling, data analysis, and/or lab experimentation) ; (2) continue to monitor polar processes with orbital assets that can differentiate between surface volatiles (3) deploy spacecraft instrumentation which will determine the long-term stability of the south polar residual cap of Mars and the density of both the seasonal and residual CO₂ ices as a function of both space and time; (4) deploy spacecraft instrumentation which will constrain CO₂ ice and snow formation and modification processes .

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Preamble:

The seasonal polar caps of Mars consist primarily of CO₂ that condenses from the atmosphere to form surface ice at high latitudes following the autumnal equinox in both hemispheres. The seasonal caps are prominent features on Mars that were first viewed by Herschel in 1784. They extend equatorward as far as

40° S in the southern hemisphere and 55° N in the northern hemisphere. Approximately 25% of the Martian atmosphere is cycled annually into and out of the seasonal caps. Consequently, the seasonal CO₂ cycle plays an important role in the planet's atmospheric general circulation. Questions about the seasonal caps that remain unresolved concern local cap properties (e.g., column abundance, volumetric density, geometric thickness, dust and water ice fraction, albedo and emissivity), energy-balance terms and CO₂ condensation mechanisms. The rate of seasonal deposition and sublimation of CO₂ ice is determined by the local energy balance, which depends on solar insolation, atmospheric properties (such as dust optical depth), emissivity and albedo of the surface, advection of energy by the atmosphere and energy storage within the regolith. The pursuit of detailed knowledge regarding the polar energy balance continues to be an important aspect of understanding Mars and its polar regions.

This white paper is intended to be a consensus of the active members of the Mars polar science community, and is the culmination of discussions held at the 3rd International Mars Polar Energy Balance and CO₂ Cycle workshop (MPEB2009) held in Seattle, WA, 21-24 July 2009. The attendees represented both America and Europe.

The limited access of landers to areas of Mars that experience polar conditions (due in part to significant technical hurdles) necessitates the continued monitoring of the polar caps from orbital platforms throughout the next decade. Even so, some sorely-needed measurements, such as surface air pressure at a high accuracy and precision, can only be obtained by a landed mission. Furthermore, all such observations must be correctly interpreted, a task which frequently requires detailed knowledge that can currently only be obtained via CO₂ ice experimentation and measurement in a laboratory setting. These sets of information will provide a more robust basis (than exists today) for the design of landed missions in the farther future.

1. Major questions and investigations within Mars Polar Energy Balance science.

Question 1: What are the detailed spectral and physical properties of CO₂ ice under Mars conditions (including plausible contaminants)?

Investigation: Determine the above CO₂ ice properties through laboratory experiments under Mars conditions.

The topical sessions at MPEB2009 were wide-ranging, including discussions of the stability of the Mars south polar residual cap, the behavior of the seasonal polar caps, the interactions of the polar caps with the atmosphere, and the thermal effects of buried H₂O ice on the net accumulation of seasonal CO₂ ice. Throughout the workshop, an overarching deficiency became apparent – the scarcity or lack of laboratory experiments regarding the physical and spectral properties of CO₂ ice (pure and as a mixture with dust and H₂O ice) under Mars conditions. Without further work in this area, numerical models will continue to have poorly constrained parameterizations of physical processes important to the polar regions, and observational data of the polar regions will continue to be loosely interpreted or even misinterpreted due to a lack of detailed understanding of the material being observed.

Question 2: What are the densities and areal coverage of the CO₂ ice that composes the seasonal and residual polar caps?

Investigation: Measure the spatial and temporal evolution (geometric thickness) of the seasonal polar caps with centimeter vertical resolution.

Investigation: Measure the topography of the south polar residual cap at 20 meter (horizontal) and centimeter (vertical) resolutions.

Investigation: Measure the column abundance of the CO₂ ice in the seasonal and residual polar caps with an accuracy of 5 g/cm².

Surface CO₂ ice emplacement can occur either as direct deposition onto the surface or as precipitation (snow) from the atmosphere aloft. The time evolution of these two modes of ice emplacement may primarily determine the seasonal cap density. Spatial and temporal density variations of the seasonal CO₂ ice are expected, but cannot be easily measured with present day observations. For example, an estimate of the volumetric density of seasonal CO₂ ice has been determined by combining MOLA altimetry, gravity measurements (radio science), and nuclear spectroscopy. Unexpectedly, the results are consistently much lower than the theoretical density for CO₂ ice, and may indicate either measurement bias or the effects of physical processes that are currently not understood. Similar results were obtained for the density of the residual polar ice. To determine CO₂ ice density as a function of space and time, NASA should send a spacecraft to Mars that is capable of two specific measurements: vertical changes in the cap height (and thus depth, given the substrate topography) during the fall, winter, and spring seasons, and a simultaneous determination of the CO₂ ice column abundance. The changes in elevation could be monitored by either a laser altimeter or by interferometric synthetic-aperture radar (InSAR). The second measurement could be accomplished with a collimated thermal-neutron detector. Since thermal neutrons are highly sensitive to the column abundance of CO₂ ice on the surface, and since thermal neutrons are readily absorbed by thin layers of material (e.g., Cd or Gd sheets), it would be possible to build a compact CO₂ ice imaging system with high spatial resolution (e.g., able to resolve spatial variations in the cap on a scale of 50-100 km), which is much closer to the resolution of the optical imaging systems than presently achieved by Mars Odyssey instrumentation (600 km resolution). Absorption of thermal neutrons by noncondensable gas (N₂ and Ar) would be corrected using microwave data (using CO as a proxy for Ar and N₂, see Question 4) or using measurements of epithermal neutrons. The column abundances would be determined to better than 5 g/cm², enabling the precise determination of density needed to test different theories on the physical form of the ice (e.g., snow vs. slab-ice vs. hoar frost) and how ice properties change with time (e.g., compaction, dust loading). Determining the geometric thickness of the ice layer to the nearest centimeter may also assist in the assessment of long term climate change, which is primarily addressed by Question 3.

Question 3: Is Mars currently undergoing climate change, and what effect does this have on polar processes and the CO₂ cycle?

Investigation: Determine the long-term stability of the south polar residual cap by establishing long-term measurements of the surface air pressure capable of detecting absolute changes of 4 Pa per Mars decade.

It has been repeatedly suggested that Mars is currently undergoing climate change, based on observations of the south polar residual cap (SPRC). Observations of hectometer-scale CO₂ ice topographic features that resemble Swiss cheese show that the “holes” are growing larger, suggesting that the residual CO₂ ice

may be experiencing net sublimation. Where the subliming CO₂ ice goes is a question of significant debate. If the CO₂ ice component of the SPRC is subliming away, then the CO₂ is going back into the atmosphere, thus raising the overall surface pressure by a few Pa per Mars decade (Haberle, 2009). However, other studies suggest that much of that CO₂ may be recondensing along the SPRC edge (e.g., Winfree & Titus, 2006, Winfree & Titus, 2007). Highly accurate and precise monitoring of the surface air pressure over long periods of time (many Mars-years) would directly address these issues. Note that the surface pressure constraint on the polar sublimation can be made by a lander anywhere on Mars.

Question 4: What is the nature of CO₂ deposition (e.g., snow or direct frosting, continuous or sporadic) and sublimation (e.g., at some depth or at the ice surface, contribution of contaminant load) in space and time?

Investigation: Determine the mixing ratios of non-condensable gases within the polar night and during the polar sublimation phase.

Mars Odyssey Gamma Ray Spectrometer (GRS) and Neutron Spectrometer (NS) data have shown that the wintertime atmosphere in the polar regions can become strongly enhanced with non-condensable gases (and are depleted in the springtime). This affects CO₂ condensation on the ground and in the atmosphere by changing the frost point, thus affecting the basic thermal structure of the atmosphere (and thereby affecting atmospheric circulation on a global scale). Because non-condensable gases are passive tracers, their time-dependent distribution can provide a great deal of information about the large-scale atmospheric circulation. It is thus very important that improved measurements of the enhancement/depletion of these non-condensable gases be made by future spacecraft. The GRS and NS Argon data have very low resolution in both space and time. Observation of trace gases other than N₂ and Ar may be feasible with spatial resolution higher than can be achieved by GRS or NS. . Carbon monoxide is an obvious candidate because it can be measured very accurately at microwave wavelengths, enabling full coverage of the high latitude atmosphere, including regions in the polar night.

Investigation: Measure and monitor clouds in the polar night, ground fogs, and CO₂ precipitation (snow).

Many of the physical expressions of the atmospheric portion of the polar energy balance on Mars occur on relatively small scales and are effectively unobservable by current passive spacecraft imagers (due to largely to a lack of illumination or contrast). However, an active imaging instrument on an orbiting platform would enable a pioneering survey of these phenomena. Such an instrument is an imaging LIDAR, with lasers tuned to the continuum and spectral features of ices. Nocturnal cloud surveys elsewhere on the planet (also poorly observable at the present time) would also be accessible to such a tool.

2. Recommendations

Recommendation 1. Create and fund a new long-term NASA R&A program, the Mars Polar Research Program (MPRP).

Motivation: The motivation for such a new program is to provide a research funding option that is willing to support inter-disciplinary studies that involve equal measures of numerical modeling, data analysis,

and/or laboratory work. The current NASA Mars R&A programs, the Mars Data Analysis Program (MDAP) and the Mars Fundamental Research Program (MFRP), do not support this flexibility. MDAP overwhelmingly funds projects in which observational data analysis is clearly the dominant investigative technique, and the Mars Fundamental Research Program only funds projects that do not have a significant observational data analysis component.

Implementation: While a separate NASA Mars R&A program for polar science is strongly preferred, we recognize that such a change may not be possible in a timely fashion and so suggest that, at a minimum:

- 1) New polar science sub-panels should be added to both the Mars Fundamental Research Program and the Mars Data Analysis Program.
- 2) Specific emphasis on and support for CO₂ ice laboratory experimentation (under Mars conditions) should be provided for.

Recommendation 2: Continued relatively comprehensive monitoring of Mars' polar regions with orbital assets.

Motivation: The extension of the relatively continuous observational record started by the Mars Global Surveyor spacecraft in 1997 is scientifically invaluable. Such measurements will enable researchers to search for interannual variations of the Mars climate (and for what causes them).

Implementation: The instrumentation necessary to continue the relatively continuous observational record started by the Mars Global Surveyor spacecraft must include the ability to determine surface and atmospheric temperatures, to differentiate between ices of different composition, to observe larger-scale weather phenomena (e.g., cap-edge dust storms), and to measure surface albedo and emissivity.

Recommendation 3: Obtain observations of Mars from orbit at a wide range of local times, while preserving an orbital inclination of between 85° and 95° to ensure polar coverage.

Motivation: With the notable exception of the Mars Express spacecraft, most observational data from orbit since 1997 have been acquired during the early to late afternoon and the pre-dawn night. Observations at other times (e.g., mid-morning) would provide useful insights into the diurnal cycle of Mars polar phenomena.

Implementation: Place a spacecraft with a suitable payload into an orbit about Mars similar to that of the Mars Reconnaissance Orbiter, but at a higher altitude, so that the nadir solar time changes throughout the mission.

Recommendation 4: All future landers and rovers destined for the surface of Mars should each be equipped with an air pressure sensor that is accurate, precise, and stable, and that records measurements of martian air pressure for as long and as often as possible.

Motivation: To ascertain whether Mars is currently undergoing a significant climatic shift (see Question 3, above). Such a determination requires a long temporal baseline (many Mars-years), and accurate and precise (capable of resolving a change as small as 4 Pa per Mars decade) absolute surface air pressure measurements. This cannot be done from an orbital platform.

Implementation: Equip each future lander and rover destined for the surface of Mars with an air pressure sensor that is accurate, precise, and stable, and that records measurements of martian air pressure for as long and as often as possible

Recommendation 5: We recommend that an orbital instrument package be sent to Mars specifically to determine formation processes and densities of seasonal CO₂ ice and snow.

Motivation: The martian polar night still holds many mysteries, particularly with respect to the phenomena associated with CO₂ phase change. These questions include the thickness of the seasonal ice as function of space and time, the formation of “cold spots” deep inside the polar night, possible convective CO₂ clouds, the enhancement of non-condensable atmospheric constituents, and the genesis of the cold and dark seasonal ice that composes the south polar “cryptic” region.

Implementation: The following orbital instrument combinations are suggested payloads that would be capable of answering questions about the nature of martian CO₂ ice processes through synergy. These packages are meant to be relatively inexpensive and lightweight to facilitate their inclusion as an add-on to an existing mission concept or as a stand-alone Discovery-class mission.

CO₂ Density Instrument Package - laser altimeter or interferometric synthetic aperture radar (InSAR), high-resolution thermal neutron imager, microwave atmospheric sounder, and high-precision radio science (ultra-stable oscillator required)

CO₂ Phase Change and Polar Night Instrument Package - Microwave atmospheric sounder, Imaging LIDAR, and high-precision radio science (ultra-stable oscillator required)

3. Opportunistic Science

The recommendations presented in this paper, while focused on understanding the Mars polar energy balance and the CO₂ cycle, would result in knowledge and understanding that benefit other aspects of Mars research.

Recommendation 2 would also result in continued quasi-comprehensive observations of the entire planet, information that is important to understanding how the Mars climate system operates and varies over time, and build up more complete observations of geological features and compositions. Recommendation 3 would additionally result in global observations of Mars' atmosphere and surface at a wide variety of local times, a feat that a NASA orbiting spacecraft has not done since the Viking missions decades ago. Recommendation 4 would also provide information to further investigate atmospheric tides, frontal passages, and dust devil frequencies. Recommendation 5 would additionally provide important information above atmospheric composition, structure, and phenomena outside the polar regions.

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